Correlation between Break Frequency and Power Density Spectrum Slope for the X-ray Source Cygnus X-2: RXTE/PCA Data

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We present results of RXTE observations of the X-ray source Cyg X-2 during 1996–1999. Its power density spectra in the 0.1–128-Hz band are fitted by a model that takes into account the power-law spectral behavior at frequencies below and above the break frequency, with an introduction of one or more Lorenz lines to describe the peaks of quasi-periodic oscillations that correspond to the horizontal branch of the Z track. The RXTE observations have revealed a positive correlation between the break frequency and the indices of the two parts of the spectrum. The spectrum steepens with increasing break frequency both above and below the break frequency.

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1. Introduction

Cygnus X-2 belongs to low-mass binaries with accreting neutron stars and is one of the brightest X-ray sources. By its spectral characteristics, Cyg X-2 belongs to the class of Z-type sources (Hasinger and van der Klis 1989), which are characterized by a Z-shaped track in the color-color diagram (CCD). In this interpretation, the spectral properties are presented in the "hard" and "soft" colors, each of which is the harder-to-softer flux ratio in the corresponding energy band. The Z-shaped track is commonly divided into three parts called branches: the horizontal (HB, the upper part of the diagram), normal (NB, the intermediate part), and flaring (FB, the lower part) branches. The position along the Z track is generally believed to be associated with increase in mass accreation rate of from HB to FB. Six sources are currently known to exhibit Z tracks in the color-color diagram: Scorpius X-1, Cygnus X-2, GX 17+2, GX 5-1, GX 340+0 and GX 349+2.

The power density spectra (Fourier transforms of the flux) of Z-type sources exhibit low-frequency (5–100 Hz) quasi-periodic oscillations (QPOs) of the X-ray flux. The names of the QPOs correspond to the branch with which their origin is identified: horizontal- (HBO), normal- (NBO), and flaring-branch (FBO) oscillations. HBOs (15–100 Hz) can also be detected in the NB spectral state. However, as one recedes from HB, the significance of the QPO peaks decreases, and they become undetectable. When moving along the Z track in its NB–FB segment, a QPO peak in the range 5–20 HZ (NBO/FBO) emerges in the power density spectra.

All three types of QPOs characteristic of the low-frequency part (< 100 Hz) of the power density spectrum have been detected for the source Cyg X-2. The NBO and FBO frequencies are very close to the break frequency, which introduces a large uncertainty in its determination. For this reason, we excluded from our analysis those observations in which NBO/FBOs were detected.

2. Data and observations

For our time analysis, we used the archival data of the PCA (Proportional Counter Array) instrument (Jahoda et al. 1996) onboard the RXTE observatory (Bradt et al. 1993) retrieved from the Goddard Space Flight Center Electronic Archive.

The X-ray source Cyg X-2 was observed by the RXTE observatory during nine series of pointing observations (10063, 10065, 10066, 10067, 20053, 20057, 30046, 30418, 40017): in March, August, October 1996, June, July, September 1997, July 1998, and in separate sessions from July until October 1998 and from January until August 1999. The observations of Cyg X-2 over this period correspond to three different observational epochs of RXTE/PCA (2, 3, and 4 in the adopted classification), for which the boundaries of the PCA energy channels were changed.

To construct the power density spectra, we used observations with a resolution of $\sim$122 μs (2^{-13} s) from the 14th to 249th PCA energy channels. This range corresponds to the flux of detectable photons up to $\sim$60 keV, whose lower limit begins from $\sim$4.3 keV, $\sim$5.0–5.3 keV, and $\sim$5.8 keV for epochs 2, 3, and 4, respectively. In this energy band, the detection of QPOs corresponding to the horizontal branch of the Z track is most significant. The power density spectra were obtained by the standard method of Fast Fourier Transform (van der Klis 1989).

We combined the observational data that were not represented by a single format for all channels from 14th to 249th. Of all the observations, we used only those during which the angle between the source direction and the Earth's horizon was more than $10°$ and the PCA axis was offset from the target by no more than $0.02°$. Among the observations of Cyg X-2, all five proportional counters were not always be switched on to record events. If the operating condition of one of the counters changed during a continuous observation (whose duration did not exceed the duration of one orbit and was, on the average, $3 - 3.5 \times 10^3$ s), then the time interval during which the total count rate changed abruptly was excluded from the analysis. Because of this filtering, the total usable observational time for Cyg X-2 was more than 4×10^5 s.

To analyze the low-frequency (< 100 Hz) variability of Cyg X-2, we constructed power density spectra in the range $0.03125 - 128$ Hz. No corrections were made for background radiation and for dead time (attributable to the instrumental delay in recording events).

3. Results

Fitting the power density spectra by a constant and by a power-law at frequencies below and above the break frequency did not yield acceptable results (according to the χ^2 test). The main reason was the absence of a sharp break and the uncertainty in the measurement of its position in the power density spectrum. The model in which at frequencies much higher ($\nu/\nu_{\text{break}} \gg 1$) and much lower ($\nu/\nu_{\text{break}} \ll 1$) than the break, each part of the spectrum could be fitted by its own power-law and in which the transition between them was not jumplike proved to be more suitable:

$$P = C \frac{\nu^{-\alpha}}{1 + \left(\frac{\nu}{\nu_{break}}\right)^{\beta}}. \tag{1}$$

Thus, $P \propto \nu^{-\alpha}$ at $\nu/\nu_{\text{break}} \ll 1$ and $P \propto \nu^{-\alpha-\beta}$ at $\nu/\nu_{\text{break}} \gg 1$.

The power density spectra were fitted in the $0.1 - 128$-Hz band by this model with the additional introduction of one or two Lorenz lines to allow for the peaks of QPOs and their harmonics. To take into account the PCA dead-time effect, which causes the total level to be shifted to the negative region (because of this effect, the Poissonian noise level subtracted from all spectra differs from 2.0 in Leahy normalization units; see van der Klis (1995) for more details), we added a constant to the general model.

Figure 1 shows typical power density spectra of Cyg X-2 for various measured break frequencies ν_{break}. The upper spectrum was constructed from the observations on August 31, 1996 (7:04–8:00 UTC) and has the following best-fit parameters: $\nu_{\text{break}} = 3.1 \pm 0.3$, $\alpha = -0.13 \pm 0.04$, $\beta = 1.45 \pm 0.03$, $\nu_{\text{Lorenz}} = 20.17 \pm 0.05$, $\nu_{\text{2Lorenz}} = 39.0 \pm 0.4$, $\chi^2 = 236$ (217 degrees of freedom). The lower power density spectrum was obtained on March 24, 1996 (2:27–3:19 UTC), which was scaled by a factor of 0.01 and has the following parameters: $\nu_{\text{break}} = 12 \pm 1$, $\alpha = 0.30 \pm 0.03$, $\beta = 2.0 \pm 0.2$, $\nu_{\text{Lorenz}} = 45.0 \pm 0.7$, $\chi^2 = 242$ (220 degrees of freedom). In Fig. 1, we clearly see a difference between the two spectra. The best fits to each of the spectra (solid curves) are shown on the corresponding scale.

For all the selected data, we obtained satisfactory best-fit parameters. The break frequency turned

out to positively correlate with the indices for the low-frequency and high-frequency parts of the power density spectrum $(0.1 - 128$ Hz$)$. In Fig. 2, the indices α and β of model (1) are plotted against break frequency ν_{break}, although in reality, the power-law spectral slope for $\nu/\nu_{\text{break}} \gg 1$ tends to $-\alpha - \beta$, and the correlation is preserved. The open circles in Fig. 2 indicate the data whose power density spectra exhibit two QPO peaks. The ratio of the peak frequencies is close to 2. As the break frequency increased, the significance of the HBO peaks reduced. The filled circles indicate the data in which only the main QPO peak was detected and a second harmonic (probably) of the main peak was either undetectable or its significance was at a confidence level lower than 3σ.

The data in Fig. 2 were fitted by straight lines. For each of the indices, we derived the following parameters: $\alpha \approx -0.18 + 0.04\nu_{\text{break}}; \beta \approx 1.23 + 0.06\nu_{\text{break}}$.

4. Discussion

For the Z-type sources (to which Cyg X-2 belongs), the typical power-law index for the part of the spectrum above the break frequency lies within the range $\sim 1.5 - 2.0$ (van der Klis 1995). In papers on a time analysis of the low-frequency part of the power density spectrum $(< 100$ Hz$)$ for Cyg X-2 (Kuulkers 1999), the variability of the source below the break frequency is assumed to be constant and is fitted by a constant. We see from Fig. 2 that the power-law slopes are equal to their assumed values for the spectra with break frequencies below ~ 10 Hz. This range of break frequencies roughly corresponds to the position of the source on the horizontal branch of the Z track. For the other spectral states (NB and FB), the break frequency is difficult to determine because of the emergence of NBOs/FBOs at close frequencies or because of the absence of a visible break in the power density spectrum (power-law shape of PDS in the range $0.1 - 100$ Hz).

Here, we analyzed all the available RXTE observations of Cyg X-2. The correlation between the power-law indices below and above the break frequency has been found for the first time. It could be anticipated that a similar correlation is a common property of the Z-type sources.

Acknowledgements

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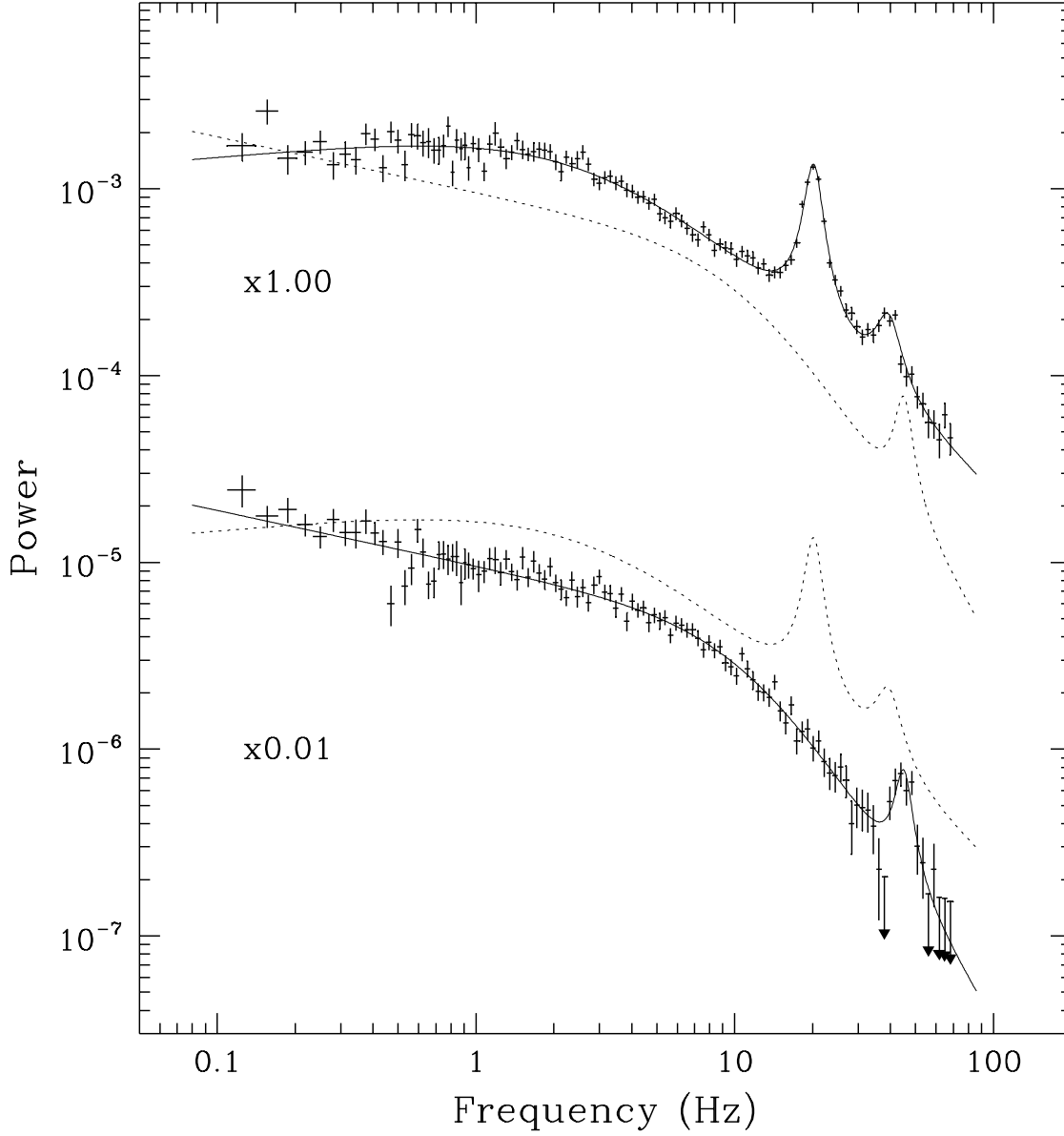
. 1.

"Cyg X-2: Correlation between Break Frequency and PDS Slope...." Two power density spectra for Cyg X-2 in the 5–60-kev energy band. The power of the lower spectrum was reduced by a factor of 100. The spectra are fitted by the break model and by Lorenz lines (solid curves); the dotted lines represent scalable fits to each of the spectra. The peaks in the upper and lower spectra correspond to the first and second harmonics of HBOs and only to its first harmonic, respectively.
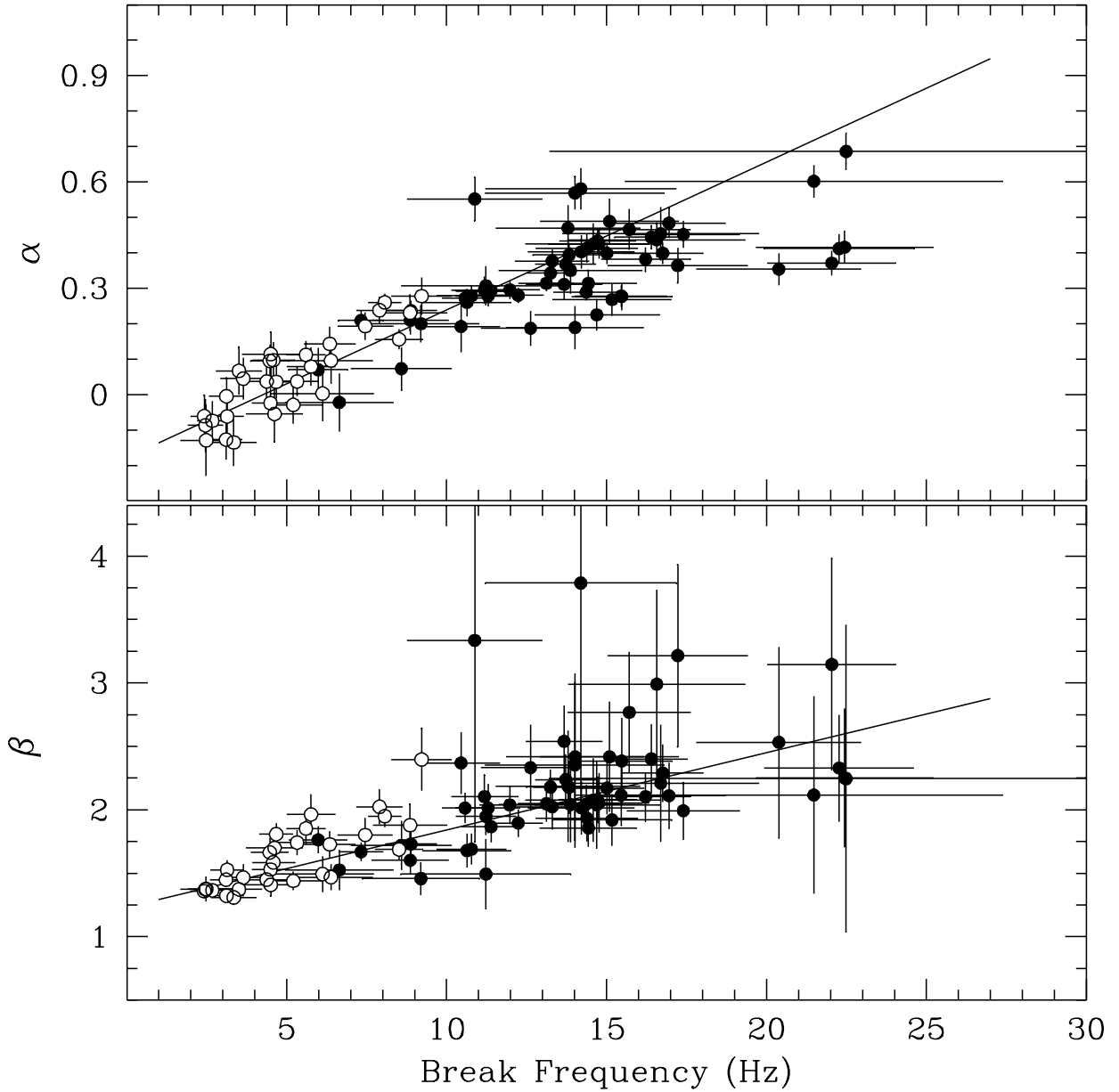
. 2.

"Cyg X-2: Correlation between Break Frequency and PDS Slope...." Model indices α and β versus break frequency. In the upper panel, the index corresponds to the fitting range at frequencies below the break; the lower panel shows an additional index that is introduced to fit a steepening of the spectrum above the break frequency. The best-fit parameters for those power density spectra that, apart from the fundamental HBO harmonic, contain the second harmonic are indicated by open circles. The solid line represents a straight-line fit to the data. For the data shown in the upper and lower panels, the straight line was drawn by taking into account errors in the break frequency and in the index β, respectively.